Robot Choreography: The Use of the Kinetography Laban System to Notate Robot Action and Motion

Paolo Salaris, Naoko Abe, Jean-Paul Laumond

On the use of Kinetography Laban to notate robot action and motion

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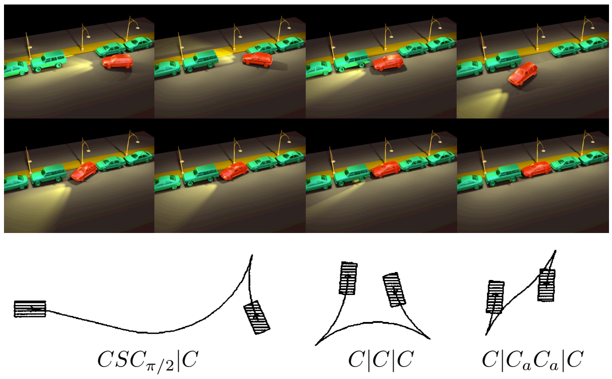
***Abstract*—Roboticists aim to segment robot actions into a sequence of motion primitives to simplify the robot programming phase. Choreographers aim to capture the essence of human body movements within a sequence of symbols that can be understood by dancers. To that extent, roboticists and choreographers pursue the same quest. We have undertaken a pluridisciplinary approach, combining a dance notation system (the Kinetography Laban system) with a robot programming system [the Stack of Task (SoT)]. Motion scores are used instead of quantitative data to compare and enlighten differences in robot and human movements. We then discuss plausible origins of these differences, taking into account the implicit rules of the Kinetography Laban system on how a movement is executed by humans. This comparison, in the light of the Kinetography Laban system, opens some challenging questions related to motion segmentation and motion naturalness.**

I. Introduction: Dance Notation and Robot Motion

A. Motion writing

How do you park a car? A way to answer the question is to consider optimality principles. Starting from the seminal work by Dubins in 1957 [1], optimal control for wheeled mobile robots has attracted a lot of attention. In [2], the problem of car parking is solved by considering a sequence of shortest length paths, i.e., the so called Reeds-and-Shepp paths [3] (Fig. 1). The shortest paths are made of two basic maneuvers: an arc of a circle (on the right/left, executed in a forward/backward direction) and a straight line (executed in a forward/ backward direction). However, not all arbitrary concatenations of these two basic maneuvers generate optimal paths. Only some of them may be optimal. In other terms, there exists a finite family of sequences of arcs and straight lines that covers all possibilities to maneuver from a start ing configuration to any goal configuration in an optimal way. Such sequences can be seen as the words of a simple motion language with an alphabet that is made of two letters that are "arc-of-a-circle" and "straight-line segment". The car parking motion can then be described as a sequence of words. With this perspective, motion planning is a matter of motion writing.

This simple car parking example perfectly illustrates the challenge of robot motion planning and control. The question constitutes the essence of robotics: how to transform an action expressed in the physical space (i.e., park the car or pick up the ball on the floor) in terms of a sequence of motions that originate in the motor control space (i.e., turn left-forward, go straight, turn right-backward, or bend the legs and then move the right hand toward the ball). The segmentation of complex movements is a fundamental step to make robot programming easier.



The words to park a car:

$$\{C|C|C, CC|C, C|CC, CC_a|C_aC, C|C_aC_a|C, C|C_{\pi/2}SC, CSC_{\pi/2}|C, C|C_{\pi/2}SC_{\pi/2}|C, CSC\}$$

Fig. 1. The algorithm in [2] computes collision-free motions for a car-like robot. The solution to park the car is a sequence of Reeds-and-Shepp elementary paths. Each elementary path is a combination of arcs-of-a-circle *C* and straight-line segments *S*. The motion can then be written as a sentence from a vocabulary of nine words made of two letters, *C* and *S*. (Photo courtesy of LAAS-CNRS)

Human beings and humanoid robots share a common anthropomorphic shape. If the ultimate goal of roboticists is to provide humanoid robots with autonomy, a quest for dancers and choreographers is to understand the foundations of human movements. In spite of completely differ ent cultures and backgrounds, both communities pursue converging objectives. In this context, it is natural to assess the potential of dance notations for decomposing complex robot actions into sequences of elementary motions. Indeed, the main purpose of dance notation is to store choreographic works and knowledge of dance techniques by translating movements into abstract symbols such as letters, abbreviations, musical notations, stick figures, and so on. In Western cultures, there are almost 90 dance notation systems, originating from their first appearance in the 15th century to the present. Among the most popular are the Kinetography Laban system, the Benesh movement notation system, and the Eshkol-Wachman movement notation system [4].

B. The Kinetography Laban system

We opted to focus on the Kinetography Laban system. This notation system scores all anthropomorphic motions independently of any behavior or any action and, hence, can be

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used with humanoid robots. The Kinetography Laban system provides a way to segment and analyze complex movements of humanoid robots. In doing this, we are able to lay the foundation for a more ambitious goal of simplifying robot programming by means of motion segmentation. In particular, we can see how the respective notions of robot action and robot motion (e.g., [5]) can be expressed within the same notation system. Our study is supported by two main experiences. The first is related to the execution of an action, such as picking up a ball. We show how the Kinetography Laban system may score the task at different levels of detail according to the objective to be reached, e.g., action execution or gesture imitation. It can range from a simple notation of a complex action to a detailed description of a simple motion. This makes the Kinetography Laban system a useful tool that allows us to capture the motion differences in executing the same action and, there fore, gives a measure of naturalness of the whole action. In our opinion, a single quantifying criterion, which should be chosen among the several available in the literature, would not reach the same objective.

However, we also demonstrate that the Kinetography Laban system might be useless in spotting the differences between two movements without the context. This is because the Kinetography Laban system operates in the physical space while the main differences between two movements might be in the motor-control space. The second experience accounts for a dance imitation that is also reported in [6]. The dance score is translated in terms of a robot program, i.e., the so-called SoT [5]. Even if the dance movements are simple and not challenging for a humanoid robot, significant differences appear between the original human movements and the robot movements. Such differences are understood by comparing the Kinetography Laban scores that describe the human motions and the humanoid robot motions. The differences between the scores provide a better understanding of what makes a movement natural.

We first review research related to the segmentation of complex movements, dancing robots, and computational scoring. We then introduce the basics of the Kinetography Laban system. This is followed by the first experience of picking up a ball. The motion performed by the HRP2 robot to pick up the ball is notated with the Kinetography Laban system. The objective is to point out the flexibility and the limitations of this notation system in expressing anthropomorphic movements with different levels of details. We then share the experience reported in [6] of translating the Kinetrography Laban score of a particular dance, known as the Tutting Dance, into a hierarchical sequence of tasks to be executed by the humanoid robot Romeo. The Kinetography Laban system is used to compare Romeo's movements with the dancer's. It appears that Romeos movements differ from the human ones. We will see how these differences might refer to recent neuroscience and biological studies.

C. Segmenting complex movements

Several reported experiments promote the idea that motor actions and movements in both vertebrates and invertebrates are composed of elementary building blocks [7]; i.e., complex movement is segmented into simple movements, and the combination of these elementary steps results in a complex action or movement, just the same as how the letters of the alphabet make up more complex ideas in the form of words. The motion segmentation of complex human movements is widely studied, and there is much research to be found in the literature. The main objective is to determine this alphabet of human movements. For instance, in [8], the authors automatically constructed a directed graph called a motion graph that encapsulated connections among the data base from human motion capture data. Motion was generated simply by building walks on the graph. In [9], the role of a parameter that characterizes the two thirds power law was investigated. This parameter was nearly constant during extended parts of the movement and only shifted abruptly at certain points of the trajectory. This was interpreted as an indicator for segmented control. In [10], the authors showed that imagined trajectories follow the two-thirds power law. These findings support the conclusion that the coupling between velocity and curvature originates in centrally represented motion planning. However, for particular cyclic or repetitive actions, such as elliptical and figure-eight patterns of different sizes and orientations performed by using the whole arm, there is no evident segmentation in the motor-control space but rather continuous oscillatory patterns [11].

In the field of learning by demonstration, a general approach for learning robotic motor skills from human demonstration was introduced [12]. By using a nonlinear differential equation to be learned to represent an observed movement, the researchers built a library of movements by labeling each recorded movement according to task and con text (e.g., grasping, placing, and realizing). In [13], a hierarchical framework capable of learning complex sequential tasks from human demonstrations was proposed. Through a task-segmentation and action-primitive discovery algorithm, both the high-level task decomposition and low-level motion parameterizations were achieved for each action. Finally, in [14], the authors proposed the use of nonnegative matrix factorization to address the problem of segmenting combinations of initially unknown human motion primitives associated with ambiguous sets of linguistic labels during training. This technique allowed the system to find the combinatorial structure of parallel combinations of unknown primitives.

II. Dance notations

Dance notation is to dance what musical notation is to music and what the written word is to drama. It is basically a symbolic description of human movements and forms by using graphic symbols and figures, numerical systems, path map ping, as well as letters and words. A recorded dance notation that describes a dance through symbols is known as a *dance score*. The most frequently used dance notation systems are the Kinetography Laban system, originally created and published by Rudolf Laban in the late 1920s, the Benesh movement notation system, invented by Joan and Rudolf Benesh in the late 1940s, and the Eshkol-Wachman movement notation system, created in Israel by dance theorist Noa Eshkol and Avraham Wachman in the late 1950s. All of them allow the notation of every kind of human movement [15], although they differ in the way they represent the human body and its movements.

The Benesh movement notation system is very similar to the modern staff music notation. It is recorded on a five-line stave from left to right with vertical bar lines to mark the transition of time. For this reason, Benesh notation is often synchronized with a musical staff. It draws the position of a dancer as seen from behind, from the top of the head down to the feet. From top to bottom, the five lines of the stave coincide with the head, shoulders, waist, knees, and feet. The system uses abstract symbols based on figurative representations of the human body. Additional symbols are used to notate the dimension and quality of movements.

Eshkol-Wachman movement notation scores are written on grids, where each horizontal row represents the position and movement of a single limb, and each vertical column rep resents a unit of time. Eshkol-Wachman movement notation represents the body as a stick figure. The body is divided at the joint level, and between two consecutive joints, a line segment is defined. A spherical coordinate system is used to relate those segments in three-dimensional space. Positions of the free end of the segment can be defined by two coordinate values on the surface of that sphere. Segment positions are written somewhat like fractions, with the vertical number written over the horizontal number, and the horizontal component is read first. These two numbers are enclosed in brackets to indicate whether the position is being described relative to an adjacent limb or to external reference points, such as a stage. Movements are shown as transitions between initial and end coordinates.

The Kinetography Laban, or Labanotation, is a system of recording all forms of movement through graphic symbols. It is used not only by dancers to write down choreography but also in every field in which there is the need to record movements of an anthropomorphic body [16]. The Labanotation uses four factors to describe a movement: the parts of the body, the space (by using direction and level symbols), the duration, and the beginning and the end of the movements.

In the Kinetography Laban system, the occurrence of movement is called vertical stroke or *action stroke*. The reading direction starts from the bottom, and a double line denotes the beginning of the movement. Any symbol before this double line refers to a starting configuration Fig. 2(a). An action can occur on the left side or on the right side of the body. To separate an action stroke that refers to one side of the body or the other, a vertical line, called the center line, is drawn and connected to the double starting line.

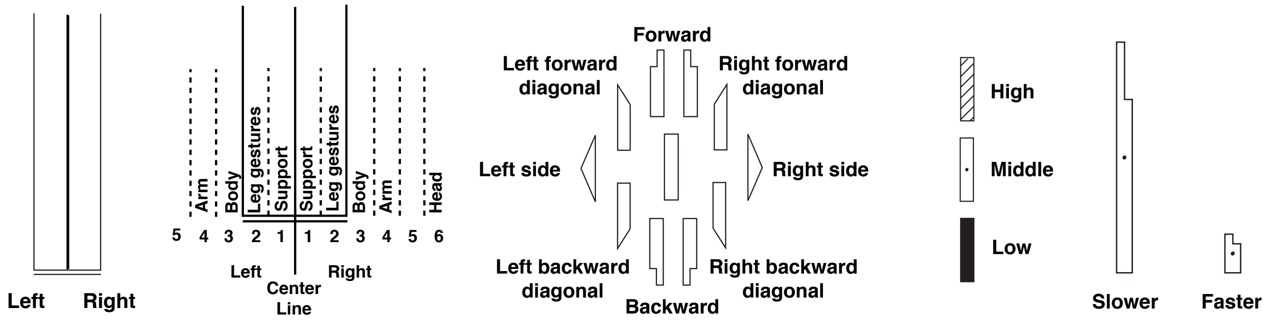
The Kinetography Laban system uses a vertical three-line staff that represents the body Fig. 2(a). The center line represents the center line of the body, dividing right and left. A staff concerns the human body and its movement. Vertical columns on each side of the central line are used for the main parts of the body. As a consequence, by placing the movement indication in one of the vertical columns of the staff, a movement for a particular part of the body is defined. Fig. 2(b) shows which part of the body each column refers to in a standard staff. In Fig. 2(b), the central columns immediately next to the center line represent the support column. Symbols placed in these columns indicate progressions of the whole body through the transfer of weight. The second columns, just next to the support columns, are used to notate leg gestures, i.e., a leg movement that does not carry weight. These columns can be used also for specific parts of the legs (the thigh, lower leg, and foot). In the third columns, outside the three-line staff, symbols describing the gestures for the upper body, the torso and all its parts, are placed. The fourth columns, immediately beyond the torso columns, are for arm gestures. As for legs, it is possible to add columns to indicate movements of the parts of the arm if needed. Finally, the last column on the right, slightly apart from the other columns, is the head column.

The main building blocks of the Labanotation are the direction symbols (Fig. 2(c)). These symbols define the spatial directions in which the part of the body should move to reach a given position. This representation of gestures suggests that, in the Labanotation, the final destination is more important than the followed path. It is important to note that the Kinetography Laban is a movement notation system, and symbols represent changes in the current body configuration produced by a movement. As a consequence, there are no symbols to represent an absence of movement.

The directions in space are specified with respect to a central point, which is called the *place* and is represented by a rectangle (see Fig. 2(c)). By slightly changing this symbol, nine main directions can also be specified with respect to the central point. Moreover, by using three different degrees of shading, three different levels (low, middle, and high) can also be specified (see Fig. 2(c)). The combination of the nine main direction symbols with the three shading levels gives rise to 27 principal directions. Notice that the direction symbols state only information about the direction and level to be reached. Once these symbols are placed in a column of the vertical staff, it is possible to know which part of the body the symbols refer to and hence the direction and level to be reached with respect to the point of attachment of that body part. For example, the whole arm is attached to the body by the shoulder. The shoulder is the point from which all directions and levels radiate. The whole arm can move with respect to the shoulder in order to reach with the extremity, i.e., the hand, the direction and level stated by the symbol. The hand is considered, in this case, the free endpoint of the arm.

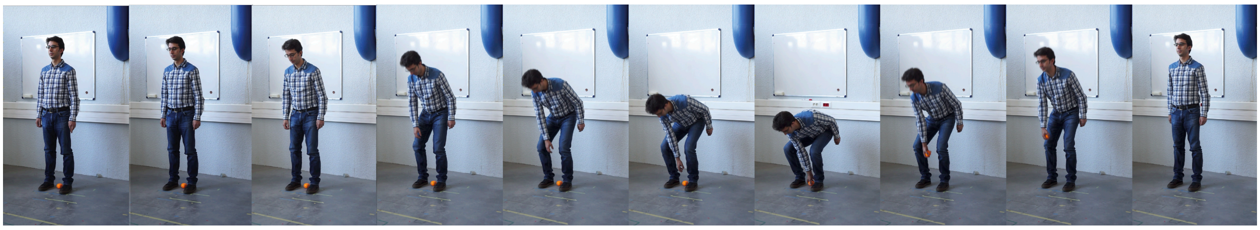
The length of the direction symbol indicates the duration of movements (Fig. 2(d)). The longer the symbol is, the slow er the movement will be. The beginning of the symbol indicates the beginning of the movement, and the end of the symbol indicates the end of the movement. To describe other details about the movement executions, particular signs can be used for other parts of the body such as fingers, the palm, or the back of the hand, and for parts of the body that have to touch other body parts or objects in the environment. An exhaustive description of all these symbols and signs is available in [16].

We chose to use the Kinetography Laban system in our work for three reasons: its geometric representation of the space around the human body, its more intuitive symbols compared to other dance notation systems to describe movements, and its simplicity in writing/reading simple scores. These attributes, for the very simple movements we have described, make the process of translating and automatizing a score in a robot programming for humanoid robots easier, even for a non expert notator.

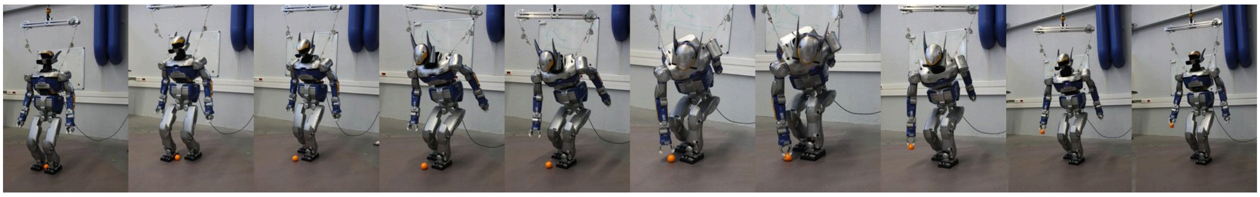


(a) (b) (c) (d)

Fig. 2. The main elements to notate a movement in the Kinetography Laban system are the three-line staff with columns for gestures. (a) The three-line staff represents the body; the direction symbols and levels, and the duration of a movement specified by the length of the symbol. (b) The standard staff show column gestures of the body parts and support of the weight; the direction symbols and levels, and the duration of a movement specified by the length of the symbol. (c) Direction symbols and levels specify the spatial directions and level in which the part of the body moves to reach a given position. (d) The symbol length indicates duration.



(a)



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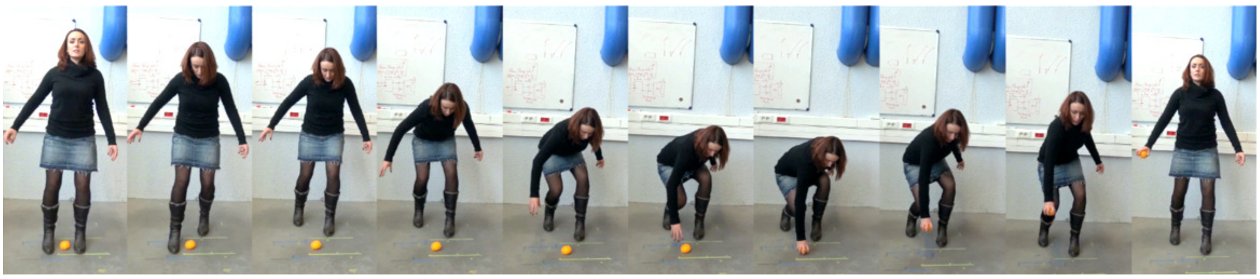
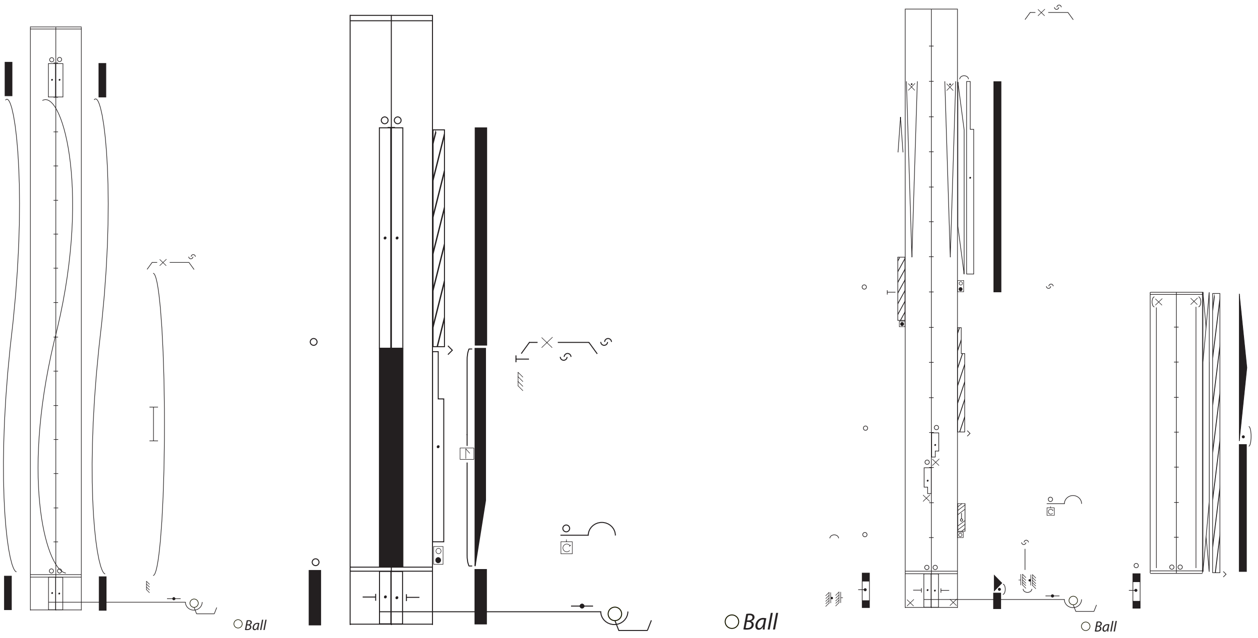


(c)

Fig. 3. To pick up the ball between its feet, the robot has to step away from the ball, while humans can grasp the ball without changing the position of their feet. This is a consequence of the mechanical differences between the human body and the HRP-2 body. (a) Paolo Salaris can pick up the ball between his feet without changing his foot position. (b) HRP-2 picks up the ball between its feet after repositioning its feet; stepping away is a direct consequence of the action "pick up the ball", even though there is no dedicated module in charge of stepping away. (c) Tiphaine Jahier executes a motion by reading the notation in Fig. 4(c), which describes the movements of HRP-2 in Fig. 3(b). For Jahier, "pick up the ball" is not an objective, but is just part of a complex motion she has to perform.

III. From Simple Action Notation to Detailed Motion Notation

Consider the simple action of grasping a ball on the floor (see Fig. 3). This relatively simple action involves complex motion requiring the coordination of all body segments. For example, the legs naturally contribute to the action, such that bending the knees becomes a direct consequence of the action "pick up the ball on the floor". The action "pick up the ball" can be notated as in Fig. 4(a). The score tells us only the initial posture, i.e., standing, as well as the arm configuration at the beginning and at the end of the action, i.e., the arms are stretched out along the body, and the initial position of the ball, which is on the floor between the feet. The notation does not mention how to pick up the ball in detail. More over, the symbols on the right side of the three-line staff describe that the



(a) (b) (c)

Fig. 4. Different Kinetography Laban scores describing the motions motivated by the action take the ball. The figures may seem obscure for readers unfamiliar with Kinetography Laban notation. Their purpose is mainly to show that differences appear. Moreover, the presence of a symbol modeling the ball shows that the notation not only deals with the movement of the human body parts, but also with the movement of the ball. (a) The notation of the action take the ball using the Kinetography Laban system. (b) A detailed description of the movement in Fig. 3(a) in the Kinetography Laban system. (c) A detailed description of the movement in Fig. 3(b) in the Kinetography Laban system.

right hand has to reach the ball by following a direct path and grasp it at a given instant. This is the only information included in the notation. This is where the flexibility of the notation in describing anthropomorphic movements of our robot, HRP2, can be used with different levels of detail, going from directly translating the sentence “pick up the ball on the floor between feet” (Fig. 4(a)) to precisely describing the movements of all body segments (Fig. 4(b) and Fig. 4(c)). It can also be used to highlight the dif ferences between two movements guided by the same action score as the one in Fig. 4(a).

A. HRP-2 takes the ball on the floor

How should we program HRP2 to pick up the ball on the floor following the Kinetography Laban score reported in Fig. 4(a)? The critical issue is to enlarge the feasible workspace of the robot arms when needed, i.e., when the object to grasp is out of the reaching space. This is done by allowing a few steps. The foot placements are determined by a continuous deformation of a virtual robot motion. The virtual robot is made of the robot augmented with a virtual kinematic chain modeling the sequence of possible foot placements. Doing so, the whole-body grasping task may be solved by a classical inverse-kinematics algorithm [17]

The final complete movement obtained by programming HRP-2 as described in [17] is shown by snapshots in Fig. 3(b). The main reason that the robot steps away from the ball before picking it up is to reach a configuration such that HRP2 can avoid a self-collision during the task. Moreover, from this new position, balance can be more easily maintained. It is important to note that there is no dedicated module in charge of the action “stepping away”, but this is a direct consequence of the action “picking up the ball”. In other words, as with human movement, the legs naturally contribute to the action.

B. Using the Kinetography Laban to compare movements

When we asked Salaris to pick up the ball without giving any constraints, he picked up the ball without changing his foot position (see Fig. 3(a)). He just bent his knees, and his right hand grasped the ball. The action of bending the knees is not explicitly expressed by the Kinetography Laban score in Fig. 4(a), just as HRP2s stepping away action was not explicitly expressed by the score. The simplest Kinetography Laban score that describes only the action pick up the ball on the floor does not have enough detail to describe precisely how a movement should be executed or to compare two different movements used to complete the same action; as a result, Salaris and HRP2 executed the same action in different ways. Perhaps another humanoid robot and another human subject would execute the same action in completely different ways. (We did not seek to determine the most natural movement for humans to pick up a ball on the floor-that is an entirely different endeavor. For our purposes, it is sufficient to observe that there are different ways to complete an action, but, without sufficient details in the Kinetography Laban score, it is not possible to predict or compare these differences.) The main objective of the score in Fig. 4(a) is to communicate to the reader the action or task to be executed; the movements behind the action are less important.

A movement score can be notated with different levels of details to account for what the notator wants to convey to the performer and for the person who is reading the score. This is not a weakness but a strength of the notation system. For

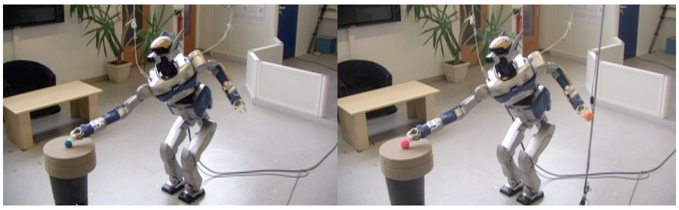


Fig. 5. On the left picture, the robot has to grasp the ball on the table in front of it. As the ball is far away from the robot but reachable without moving the feet, the robots bends forward. However, to maintain balance, the left arm moves behind. In the figure on the right, the robot has to grasp a ball in front of it and a ball behind (of course the ball behind has been intentionally placed at the end position of the left hand on the left picture). Is it possible to spot the differences between these two motions by using the Kinetography Laban?.

instance, the score depicted in Fig. 4(b) is the detailed notation of Salaris's movement. The notation describes his manner to take the ball with many details. It includes how he reaches to the floor with the hand (e.g., the rotation of the torso), how he grasps the ball (e.g., the choice of the right hand), the direction of his gaze, and the motion timing. Fig. 4(c) shows a notation of HRP2's entire movement. It includes exactly the same level of details as the score in Fig. 4(b). By comparing the two Kinetography Laban scores, it is possible to appreciate that these two movements are different, and that the HRP2 movement appears to be much more complex. Notice that HRP2 did not execute Salaris's score because of its mechanical constraints/limits.

Finally, we asked Jahier, an experienced Kinetography Laban notator, to read the score in Fig. 4(c) concerning the detailed motion of HRP2 and to perform the motion only according to the score (see Fig. 3(c)). she was not aware of the objective of the study and she did not see HRP-2 before executing her motion. She was not aware of the objective of the study, and she did not see HRP2 before executing her motion. For Jahier, the action "pick up the ball on the floor" is not an objective; rather, it is just part of a complex motion she has to perform. The motions executed by Salaris and Jahier differ, even though the underlying action is exactly the same in both cases, i.e., grasping the ball. Salaris's motion reflects the intention to grasp the ball. His motion is not constrained by an objective. Jahier's motion reflects the imitation of a motion, in that grasping the ball is only a side effect of the motion.

These examples show how flexible the Kinetography Laban system is as a motion-notation system. According to the objective of the notator, the score may encode different levels of detail, ranging from a simple description of a complex action to a detailed description of a simple motion.

From previous experience, we can deduct that the Kinetography Laban system can be used to compare humanoid robot actions and movements with human actions and movements. A single quantifying criterion, chosen from among several available in the literature, would not reach the same objective. However, it is important to recall that the Kinetography Laban system translates a movement in symbols by looking only at the physical space. This might complicate the comparison of movements or make it impossible a description of the context. In some cases, the comparison might be simpler in the motor-control space. Let us consider, for example, the two scenarios reported in Fig. 5 taken from [18]. In the first scenario, the humanoid robot has been programed to reach with the right hand the ball on the table in front of it. As a secondary effect of the main task, the left hand moves behind the robot to maintain the robots balance. In the second scenario, the robot not only has to grasp the ball on the table in front of it, but it also has to grasp a second ball behind it (the ball behind the robot has been intentionally placed at the end position reached by the left hand as a result of the movement required to maintain balance). By looking at the two movements of the robot, it is not possible to spot the differences. Only the context, i.e., the presence of two balls to be grasped instead of just one, provides some hint about the intention of the movement.

The Kinetography Laban score describes movement as it appears to the notator's eyes. Depending on the level of detail, however, the two movements may be notated differently. Let us assume that a low level of detail is used, similar to the score of Fig. 4(a) which describes the action of "picking up a ball on the floor". We can see that, in the first scenario, the movement of the left arm will not be notated. Indeed, the main action to write down is to grasp the ball on the table; the action of the left arm to maintain balance is not included.

In the second scenario, both actions are written down. If a high level of details is used, the movements of all parts of the humanoid robot will be notated, and, as they appear very similar, the only difference will be the presence of two balls in the second scenario and only one ball in the first scenario. By using a high level of detail, the actions of grasping the balls are only part of a complex movement. However, results in [18] show that the movements of the two scenarios can be distinguished in the proper task space. The presented method takes advantage of the knowledge of the task the robot is able to perform and how the motion is generated from this set of known controllers to reverse-engineer an observed motion. The method is based on the projection operation into the null space of a task to decouple the controllers. In other words, access to the motor-control space to distinguish similar look ing movements is exactly what the Kinetography Laban system, which is designed to describe human movements, is not able to do [18].

IV. On the naturalness of movements: the "implicit rules" of the Kinetography Laban

In [6], a simple Kinetography Laban score of the Tutting Dance sequence, i.e., a dance that mainly involves arm and hand movements, has been scored according to the Kinetography Laban system and translated in robot motion (Fig. 6). The method is based on the Stack of Tasks (SoT), a robot programming system introduced in [19]. The 27 principal direction symbols used to describe the Tutting Dance [6] are the starting point to translate the Kinetography Laban score in the SoT. In other words, depending on the current configuration of the humanoid robot Romeo, each principal direction symbol is translated as a task in the operational space. Indeed, each direction symbol specifies the main directions and levels with respect to the point of attachment of the body part to which the symbol refers (see Fig. 2(c)). As a consequence, with respect to the point of attachment, it is possible to associate a homogeneous transformation matrix to each symbol that specifies both the position and orientation of a reference frame at that direction and level. Based on the current position of the body part and the desired position specified by the principal direction symbols, a task function is defined as the error in terms of both rotation and translation between the current position in space of the reference frame attached to the free end and the desired one. The SoT software [20] is then used to determine suitable control signals for the motor of the robot such that the error becomes zero, while guaranteeing other tasks at the same time (e.g., maintain static equilibrium, maintain the static position of the parts of the body that are not involved in the movement, and so on). This results in a dynamic hierarchy of tasks.

Once the whole movement is translated in the SoT, suitable control signals are sent to the motor of a simulated version of the humanoid robot Romeo, and the whole movement has been reproduced by the robot. One of the main differences

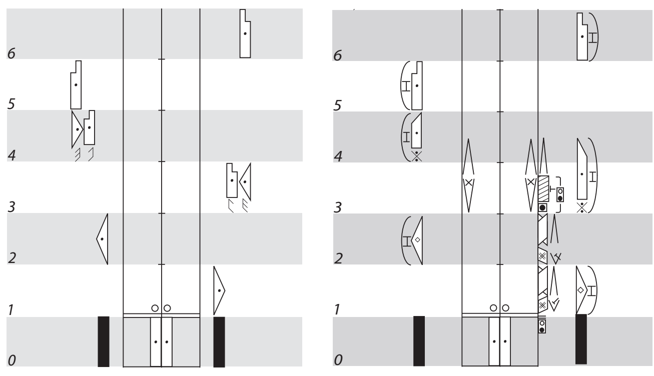


Fig. 6. A comparison between the Kinetography Laban score of the first part of the Tutting Dance executed by a dancer and Romeo. The main difference is in the path of the free end of the arm (here considered to be the wrist). The path for Romeo is along a straight line from the initial position to the final position (see Fig. 7). There are also several movements of the torso. Moreover, the arm is a little curved during the movement, and the gestures are slightly overlapped (the movement in the original score is a "staccato" movement). (a) The Kinetography Laban score for a dancer and (b) the Kinetography Laban score for Romeo.

between Romeo's movements and human movements from the Kinetography Laban perspective (i.e., in terms of symbols and signs in the Kinetography Laban score) is the arc with the capital letter "I" to the side of each direction symbol inside the arm columns (see Fig. 6 and [6] for details about other differences). This new symbol indicates a description of the path that the free end of the arm is now executing, i.e., a straight line. In the context of the Kinetography Laban system, the addition of this sign to the side of each direction symbol con strains the movements of the free end of the part of the body to which the symbol refers along a straight line. Without that sign, the movement adheres to the implicit rules of the Kinetography Laban system that, after several years of analysis, reflect the natural way of moving.

The direction symbols state only information concerning the element of direction. Once they are placed in the appropriate column of the vertical staff, it is possible to determine which part of the body has to move. Moreover, depending on the cur rent configuration of the body, information about the path that the free end of the body part to which the symbol refers can also be obtained, giving rise to so-called implicit rules.

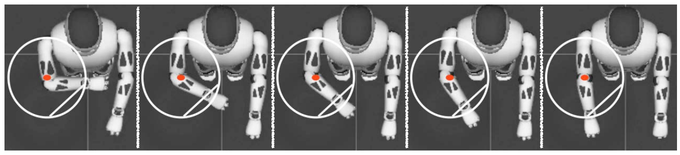


Fig. 7. A sequence of snapshots for the movement at step 6 in the Laban score of Fig. 6(a). The free end of the right arm moves along a straight line between the starting position and the desired one. This gives rise to other undesired and unnatural movements. In this case, the elbow (red point) does not remain at a fixed position in space.

The information about the movement execution is achieved from the concept of degree-distance between direction symbols. Each symbol indicates a point to be reached around the point of attachment of the body part (e.g., the shoulder for the arm). Symbols that correspond to adjacent points in space are at a first-degree distance from one another (see Fig. 8). For example, if the arm moves from forward-middle to the adjacent right-front diagonal point, this is a first-degree distance. In this case, the free end of the arm, i.e., the hand, describes an arc-of-circle on the surface of the sphere whose center is the shoulder. This is called a peripheral movement in the Kinetography Laban system. All movements between first degree distance points produce this type of path. If the

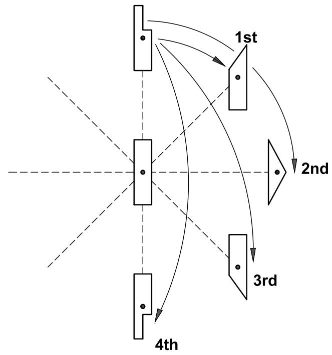


Fig. 8. Degree of distance between direction symbols. According to this distance, the free-end of the arm has to generate a *peripheral movement*, a *transversal movement* or a *central movement*.

arm moves from forward-middle to side (right or left)middle, then the starting and ending points are at a second-degree distance (see Fig. 8) and the hand describes a quarter of circle with respect to the shoulder. In this case, we also obtain a peripheral movement. All movements between second-degree points are performed without any special flexion of the arm unless otherwise specified with the addition of particular signs.

If two points are at a third-degree distance, the hand moves along a trajectory close to the body. This movement is not a peripheral path. Indeed, the arm is slightly bent, and the free end of the arm takes a path between periphery and center (in place). This is called an *intermediate situation* or a *transversal movement*.

Finally, diametrically opposite points are at a fourth-degree distance. This is the case when the arm moves from forward-middle to the extreme opposite direction, i.e., backward-middle. The arm moves back into place, and then it extends outward again. These types of movements are called *central movements* in the Kinetography Laban system.

The control laws used to move Romeos arms do not generate all of these various movements. Instead, the control laws implemented in Romeo simply reduce the distance between the current configuration of the free end of a body part and the desired position. The resulting path for the free end of a body part is a straight line with a noticeable loss in naturalness. To generate a straight-line path, other undesirable and unnatural body movements are necessary. To avoid such unnatural movement, an ad hoc control law that moves the free end of a body part along peripheral, central, or transversal movement might be determined. The implicit rules of the notation come from several years of observations, and they are based on the naturalness of human movements and the mechanical structure of the body. As is often conjectured in robotics, an optimality principle might be inherent in human movements [5]. Thus, it would be interesting to understand this principle, to express it in a suitable mathematic manner, and then to use it to determine suitable control laws for humanoid robots.

One of the main limitations in translating the Kinetography Laban score in humanoid robots obtaining movements that resemble the human movements. Several biological studies have sought to identify the principles that explain, among all possible movements, the ones humans perform in every day tasks [21]. In [22], a robotic approach for the synthesis of human motion using a task-space framework is presented. In this framework, the authors showed that task-driven human motions come from the physiomechanical advantage of the human musculoskeletal system under physiological constraints. Regarding arm movements only, the coordination of voluntary human arm movements was presented as an objective function as a measure of performance for any possible planar multi-joint arm movement [23]. By using dynamic optimization theory, the authors showed that the objective function is the square of the magnitude of a jerk of the hand integrated over the whole movement. As a result, the main objective of motor coordination is to reproduce the smooth est movement of the hand. If the arm moves on a vertical plane or in a manner that is not only on the horizontal plane, the force of gravity plays an important role. To move against gravity is a very different proposition compared to moving along the gravity vector. In [24], the authors tried to under stand how the central nervous system plans and controls vertical arm movements. By using the optimal control theory, the experimental findings can be explained in terms of the minimization of an optimal motor planning (minimum absolute work-jerk), which integrates the direction and the magnitude of gravity torque and minimizes the absolute work of forces (energy-related cost) around each joint.

Another critical challenge in motor control is how the central nervous system deals with redundancy. One way to sim plify the motor control is to combine several degrees of freedom into synergies. In [25], by principal component analysis, the authors showed this behavior during fast, unrestrained, and untrained catching movements. This provides a reduction of the number of dimensional motor spaces into a few dimensional control spaces, giving rise to a simplification in the optimization procedure.

Reproducing a human movement in a humanoid robot is a known challenge. The Kinetography Laban score system can be used to simplify the robot programming phase. In doing this, however, two issues must be taken into account. First, the human body and the humanoid robot body differ, and this influences movement. Salaris and HRP2 pick up the ball on the floor between the feet in different manners. The main reason is that the body of HRP2 does not allow it to move its hand between its feet in order to avoid self-collision. HRP2 is therefore forced to step away and establish a configuration that avoids self-collision and maintains balance. Moreover, to program HRP2 to pick up the ball on the floor, we may benefit from the score in Fig. 4(a) but not from the other score. Indeed, the score in Fig. 4(c) does not take into account the mechanical limits of HRP-2, while the second score in Fig. 4(b) is too detailed and hence complex to be programmed. The level of details adopted in the Kinetography Laban score is a critical issue. Moreover, human motion notations are based on the kinematic structure of the human body. Adapting the notation to another structure is certainly possible, but it is a challenge by itself. Second, there is the challenge of the naturalness of a movement. In the Kinetography Laban system, the rules to move the hand in a given direction have been defined and described on the basis of extensive experience in observing human movements. These described notations, however, are not a priori influenced by causality principles, i.e., by the origin of the movement, which takes place in the muscle control space. It is not necessary to tell a dancer what muscles he or she has to activate to perform a desired movement. In humans, muscle activation is an unconscious process. With the fundamental problem of invert ing actions expressed in the physical space into motor controls, roboticists must address the causality principle. This is why, like neurophysiologists, roboticists try to exhibit general movement laws to explore plausible causality principles. Combining the minimization of suitable objective functions, extracted from human movement analysis, and the concept of synergies to reduce the variables to be optimized might be an interesting approach to bridge the gap between dance notation with their rules of naturalness and robot programming.

V. Conclusions

It is important to stress that we did not intend to propose a new programming system for humanoid robots. Instead, we sought to disseminate in the robotics community the Kinetography Laban system as a way to segment and analyze complex movements of humanoid robots. In particular, we have shown how the respective notions of robot action and robot motion can be expressed within one notation system and how the Kinetography Laban system can be used to com pare human and robot movements. Moreover, we have also shown how the SoT can be used to translate a dance score into robot motions. By comparing the Kinetography Laban scores that describe the human and humanoid robot motions, new perspectives about what makes a movement natural by considering the implicit rules of the Kinetography Laban system have been also drawn.

We have seen that dance notation and robot program ming pursue two different goals in two different spaces. Dance notators mainly address the physical space, while roboticists tend to bridge both physical and motor spaces. In spite of these differences, the various experiences presented in this article may open a pluridisciplinary research perspective based on a mutual understanding between robotics and movement science as addressed by choreographers and dancers. In particular, the relationship between action and motion, as well as their symbolic and computational foundations, are complementary as developed by dance notation practitioners and roboticists. The dialogue deserves to be more deeply explored.

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